ORNL/TM-2018/14
SNS-RAD-MS-TR-0017, R00

SNS Resonance Control Cooling Systems and Quadrupole Magnet Cooling Systems DIW Chemistry

Karoly Magda

January 2018

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Research Accelerator Division
Central Cooling Systems

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Date Published: January 2018

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ACRONYMS AND DEFINITIONS

Al	aluminum
Ca	calcium
CCL	Coupled Cavity Linac
Cl	chlorine
Cl^-	chloride ion
CO_3	carbonate
Cr	chromium
Cu	copper
DIW	deionized water
DTL	Drift Tube Linac
DVB	divinylbenzene
EDS	energy dispersive spectroscopy
EPICS	Experimental Physics and Industrial Control System
Fe	iron
gal	gallon
GPM	gallons per minute
H	hydrogen
H_2O	water
HCO_3	bicarbonate
K	potassium
KL	klystron
LANL	Los Alamos National Laboratory
LEBT	Low-Energy Beam Transport
linac	linear accelerator
MBD	mixed bed demineralizer
MEBT	Medium-Energy Beam Transport
Mg	magnesium
Mn	manganese
MΩ	megaohm
Na	sodium
NH_2Cl	chloramine
Ni	nickel
NO_3	nitrate
O	oxygen
OH	hydroxide
ppb	part per billion
PV	process variable
QMCS	Quadrupole Magnet Cooling System
RCCS	Resonance Control Cooling System
RFQ	Radio-Frequency Quadrupole
SCL	Superconducting Linac
SEM	scanning electron microscopy
Si	silicon
SiO_2	silica
SNS	Spallation Neutron Source
SO_4	sulfate
TDS	total dissolved solids
XRD	x-ray diffraction

ACKNOWLEDGMENTS

I would like to thank Jim Schubert, the Central Cooling Systems design engineer, for contributing the description of the SNS RCCS/QMCS DIW cooling loops chemistry control to this report. Jim shared his experience with DI water chemistry from his long service at ORNL/SNS and provided the Accelerator cooling systems DI water chemistry history. He also provided the concept and design of portable carts with the mounted instrumentation for chemistry data collection.

I would like to also thank Traven Proveaux, a student intern during the summer of 2016, for entering collected DI water chemistry data into sheets and organizing them. He also made a large number of charts.

ABSTRACT

This report focuses on control of the water chemistry for the Spallation Neutron Source (SNS) Resonance Control Cooling System (RCCS)/Quadrupole Magnet Cooling System (QMCS) deionized water (DIW) cooling loops. Proper cooling-water chemistry is essential to preserving the DTL and CCL structures during their design lifetime. Appropriate water chemistry will protect cooling-water passages and brazed joints of the structure from erosion, corrosion, and fouling. The RCCS/QMCS DIW chemistry is managed by sidestreams built into the cooling loops; chemicals are not used.

Data collected from spring 2013 through spring 2016 are discussed, and an operations regime is recommended. During the evaluation period, the pH, dissolved oxygen, and water resistivity of the cooling water were observed. The data were collected by instruments mounted on mobile chemistry carts, which were moved from one RCCS/QMCS DIW skid to another. During data reading, operational corrections were done on the polishing loops to improve the water chemistry regime. Therefore some trends changed over time.

It was found that the RCCS operates with an average pH of 7.24 for all lines (from 7.0 to 7.5, slightly alkaline), the average low dissolved oxygen is in the area of < 36 ppb, and the main loop average resistivity of is > 14 MΩ-cm. The QMCS was found to be operating in a similar regime, with a pH of about 7.5 (slightly alkaline), low dissolved oxygen in the area of < 45 ppb, and main loop resistivity of 10 to 15 MΩ-cm.

It is recommended that the cooling loops operate in a regime in which the water has a resistivity that is as high as achievable, a dissolved oxygen concentration that is as low as achievable, and a neutral or slightly alkaline pH. An RCCS/QMCS chemistry guidance document published in May 2017 describes and standardizes the methods and practices for water chemical treatment for the SNS RCCS and QMCS.

It is very difficult to accurately measure the pH, dissolved oxygen, and water resistivity in highly pure water. Therefore, a regularly scheduled calibration program will be established for the instruments. Recommendations are given at the end of the report on how to run the RCCS/QMCS cooling water chemistry.

Chemical analysis of the material trapped by the polishing loop prefilters is conducted twice a year. The analysis and its benefits are described in Chapter 9.

1. INTRODUCTION

The Spallation Neutron Source (SNS) linear accelerator (linac) consists of a warm linac and a cold linac. The first component in the warm linac is the Drift Tube Linac (DTL); the second is the Coupled Cavity Linac (CCL). The cold linac [i.e., the Superconducting Linac (SCL)] is composed of the Medium Beta and High Beta sections.

The Resonance Control Cooling System (RCCS) consists of six DTL cooling loops and four CCL cooling loops [1,2,3]. The cooling loops cool the accelerator components in the linac tunnel. The RCCS water systems have two functions: (1) to control the structural geometry by controlling the temperature and thus controlling resonance and (2) to keep the components from overheating. The Quadrupole Magnet Cooling System (QMCS) cools the CCL and SCL magnets. It has only one function: to remove the heat generated in the magnets by beam focusing in the linac tunnel. The RCCS/QMCS deionized water (DIW) chemistry is managed by sidestreams built into the cooling loops; chemicals are not used. (See Appendix A for a description of the filter beds used to condition the water.) The eleven cooling-system pump skids and the associated technical components are in the Klystron Gallery.

The DTL structure is housed in tunnel at the very beginning of the linac, in the extension of the Front End. The Front End components are the ion source, Low-Energy Beam Transport (LEBT), Radio Frequency Quadrupole (RFQ) [4,5], and Medium-Energy Beam Transport (MEBT). The layout of the main components of the SNS accelerator is shown in Figure 1. The position of the DTL and CCL are shown in relation to the accelerator. The image was captured from the Experimental Physics and Industrial Control System (EPICS). The DTL and CCL cooling structures are shown in Appendix B, Figures B-1 and B-2, respectively. The QMCS magnet cooling structure is shown in Figure B-3

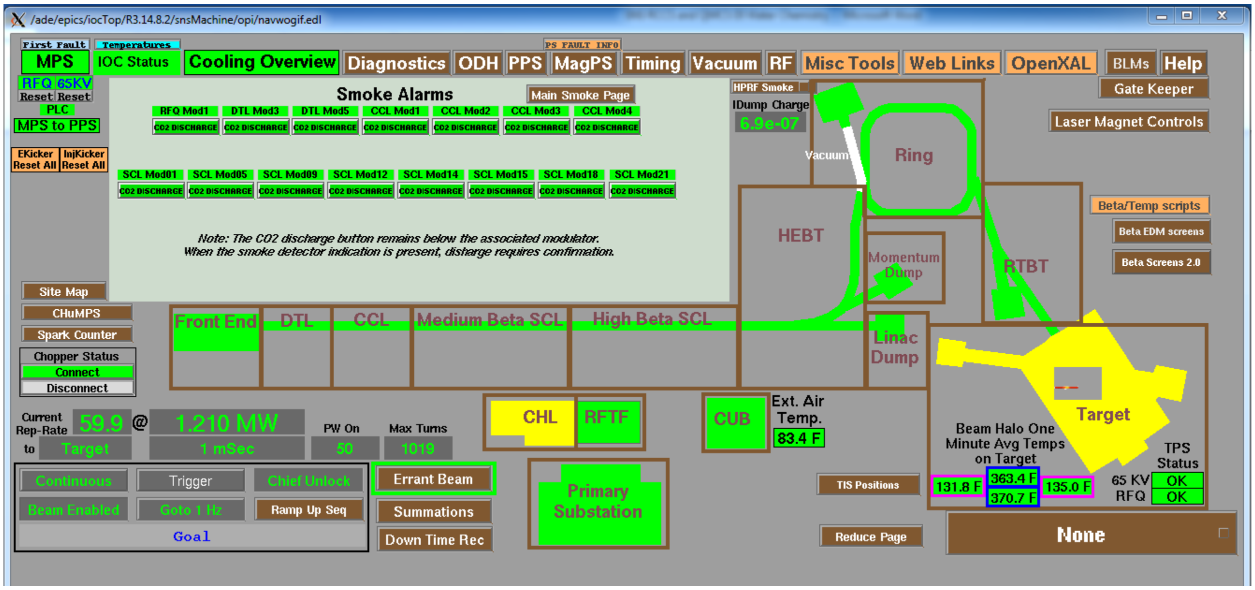

Figure 1. SNS accelerator layout on the Experimental Physics and Industrial Control System (EPICS) main screen.

2. RCCS DTL/CCL AND QMCS DIW QUALITY SPECIFICATIONS

The Mechanical Engineering Group at Los Alamos National Laboratory (LANL) defined the specifications for the SNS DTL/CCL deionized water (DIW) cooling and resonance control and designed, constructed, and tested it. Typical parameters used to measure or quantify water purity include pH, electrical conductivity, total suspended and dissolved solids, dissolved oxygen content, and radioactivity. The water quality requirements for the RCCS DTL/CCL and the QMCS are specified in the Final Design Report [3]. The RCCS/QMCS DIW system parameters and required values are listed In Table 1.

Table 1. RCCS/QMCS DIW system requirements.

Parameter	Required value
Minimum flow rate through purification loop (GPM)	2.6–3.1 (1% to 5% total through the skid)
pH	8 ± 1
Resistivity (MΩ)	10–14
Dissolved Oxygen (ppb)	< 20
Particulate size (µm)	≤ 1
Corrosion (mil/year)	≤ 0.5

Source: J. D. Bernardin, R. Brown, G. Bustos, M. Crow, J. Gioia, W. Gregory, M. Hood, J. Jurney, D. Katonak, Z. Konecni, P. Marroquin, I. Madalen, A. Owen, L. Parietti, and, and R. Weiss, *Spallation Neutron Source Drift Tube Linac Water Cooling and Resonance Control System Final Design Report*, SNS-104020500-DE0001-R01, Los Alamos National Laboratory, Los Alamos, New Mexico, October 25, 2001.

Flow and volume parameters to protect the cooling channels from erosion are specified in the LANL document. The water flow velocity limits are 2.5 m/s (8.2 ft/s) for tees and elbows, and 5 m/s (16.4 ft/s) for the straight sections. The temperature range is 10° to 25°C.

The parameters that were used for designing the water purification systems for all RCCS/QMCS DIW systems are listed in Table 2 [3]. The table includes the system flow rates, suggested flow rates for the purification system, and system volumes. At that design phase, LANL projected separate cooling systems for the CCL and SCL magnets; however, it was later decided to use one system (the QMCS) to cool all the magnets in the CCL and SCL. The copper structural material at SNS is low-oxygen copper (UNS No. C10100).

Table 2. RCCS/QMCS deionized water system design flow and volume.

Unit	ID number	System flow rate (GPM)	Purification system flow range (GPM)	System volume (gal)
1	DTL-1	119	1.2–6.0	256
2	DTL-2	161	1.6–8.1	281
3	DTL-3	234	2.3–11.7	281
4	DTL-4	214	2.1–10.7	281
5	DTL-5	198	2.0–9.9	281
6	DTL-6	182	1.8–9.1	281
7	CCL-1	219	2.2–11.0	308
8	CCL-2	257	2.6–12.9	308
9	CCL-3	257	2.6–12.9	308
10	CCL-4	257	2.6–12.9	308
11	CCL-Mag	61	0.6–3.1	359
12	SCL-Mag	TBD	TBD	912

Source: J. D. Bernardin, R. Brown, G. Bustos, M. Crow, J. Gioia, W. Gregory, M. Hood, J. Jurney, D. Katonak, Z. Konecni, P. Marroquin, I. Madalen, A. Owen, L. Parietti, and, and R. Weiss, *Spallation Neutron Source Drift Tube Linac Water Cooling and Resonance Control System Final Design Report*, SNS-104020500-DE0001-R01, Los Alamos National Laboratory, Los Alamos, New Mexico, April 4, 2001.

3. CURRENT CHEMISTRY PARAMETERS

The chemistry parameters and associated values for the RCCS/QMCS cooling water are listed in Table 3 [6].

Table 3. RCCS/QMCS cooling water chemistry parameters and values.

Parameter	Value
Resistivity (MΩ-cm)	> 12
Dissolved oxygen (ppb)	< 20
pH (dictated by resistivity and dissolved oxygen)	6.5–8.0
Flow rate through the polishing loop (GPM)	
For all DTL and CCL systems	4
For QMCS systems	6

Source: K. Magda, *RCCS/QMCS Chemistry Guidance Document*, 2017.

The RCCS/QMCS systems current flow rates under 1.2 MW beam power as of July 31, 2017, are listed in Table 4.

Table 4. RCCS/QMCS cooling water systems current flow

Unit	ID number	Flow rate (GPM)
1	DTL-1	118
2	DTL-2	185
3	DTL-3	243
4	DTL-4	219
5	DTL-5	200
6	DTL-6	195
7	CCL-1	221
8	CCL-2	233
9	CCL-3	249
10	CCL-4	241
11	QMCS	257

4. RCCS/QMCS SYSTEM DESCRIPTION

4.1 RCCS COOLING SYSTEM HISTORY

After startup of the RCCS/QMCS DIW system, the polishing loop protocol went through several phases with no chemical treatment, and chemicals were not added to the water. The water purification is done only by the polishing loop, which includes filters, ion exchangers, and ultraviolet (UV) lights.

Initially, the DIW was polished by using dissolved oxygen, cation, and mixed-bed resin bottles and filters. During the first year of operation the water resistivity was kept at 8 MΩ-cm. In second period it was increased to 10 MΩ-cm, and in the third year it was increased to 12 to 13 MΩ-cm. In July 2014 it was increased to be as high as was achievable (15 MΩ-cm). The water resistivity was increased with the goal of meeting the design parameters for DIW (i.e., high resistivity, close to neutral pH, and low dissolved oxygen).

4.2 DIW PURIFICATION BASICS

The purification system for the linac RCCS/QMCS cooling water was designed with the intent of minimizing erosion, corrosion, scaling, biological growth, and hardware activation. The SNS RCCS/QMCS water systems operate under conditions of low oxygen, high resistivity, and close to neutral pH. The pH is a function of resistivity and oxygen concentration in the water. The RCCS/QMCS water purification system consists of two polishing loops: the polishing loop of the main circulating loop and the makeup water polishing loop. The makeup loop is activated when water is added to the main loop. The quality of the water in the main loop is maintained by polishing a small percentage of water flow through a side polishing loop.

A typical DIW system consists of the following components:

- prefilters
- ion exchangers
  - carbon
  - deoxygenation
  - cationic
  - anionic
  - mixed-bed
- ultraviolet radiation
- afterfilters

4.2.1 Water purification using DIW Ion Exchangers

Three types of ion exchanger resin beds are used at SNS for purification of RCCS/QMCS DIW; all are products of ResinTech [7]. (See Appendix A for photographs and descriptions of the resins in carbon, oxygen-scavenger, and mixed-bed resin beds.)

Special resins in the DIW ion exchanger remove positively and negatively charged ions (ionized minerals and salts) from the water. The resins are synthetic materials composed of small beads and can be cation or anion resins. Cation resins exchange a chemically equivalent amount of hydrogen (H) ions for unwanted positively charged contaminants in the water [calcium (Ca), sodium (Na), magnesium (Mg), iron (Fe), manganese (Mn), and potassium (K) ions]. Anion resins exchange hydroxide (OH) ions for negatively charged contaminants in the water [sulfates (SO_4), chlorides (Cl^-), carbonates (CO_3), bicarbonates (HCO_3), nitrate (NO_3), and silica (SiO_2)].

Cation and anion resins can be combined into a mixed bed. The cation resin removes positively charged ions and releases H^+ ions; the anion resin removes negatively charged ions and releases OH^- ions. The H^+ and OH^- ions unite to form pure water molecules.

Activated carbon bed resins are used to remove Cl^-, chloramines (NH_2Cl), and dissolved organic contaminants from the potable water (city water) for the DIW system makeup.

The dissolved oxygen is removed from the DIW by using ResinTech SIR-800, a strongly basic gel resin that contains sulfite (SO_3). Oxygen is removed from the water by converting the sulfite to sulfate (SO_4).

4.3 RCCS PURIFICATION SYSTEM COMPONENTS

The RCCS system consists of the pump skid housed in the Klystron Gallery with the associated components. The accelerator structure components are housed in the linac tunnel. The main components of the QMCS cooling system are the pump skid housed in the Klystron Gallery. The magnets are housed in the CCL and SCL sections of the linac tunnel.

4.3.1 Polishing Loops

Each RCCS closed loop has its own sidestream polishing loop. The typical DTL and CCL RCCS closed polishing loop consists of the following components (see Figures 2 and 3) [6]:

- 5 µm prefilter
- dissolved oxygen ion exchange resin bottle
- two mixed bed demineralizer ion exchange resin bottles
- UV light
- 1 µm afterfilter

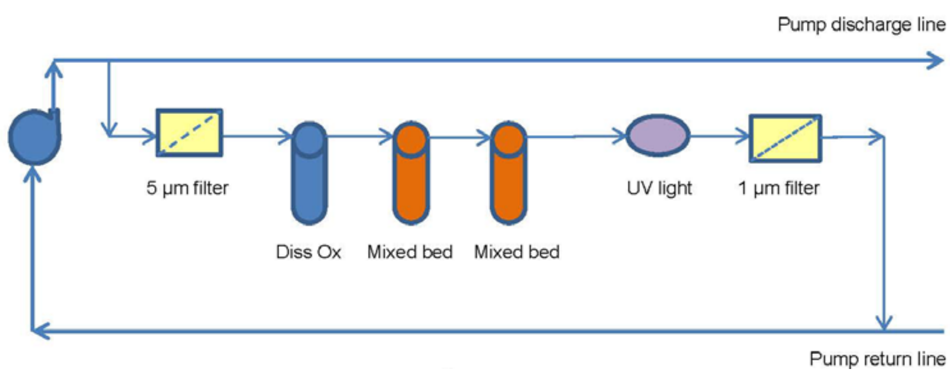

Figure 2. RCCS polishing loop components.

Figure 3. A typical RCCS DIW polishing loop.

The QMCS polishing closed loop differs from the RCCS system loops only because it has two dissolved oxygen ion exchanger resin bottles. The reason is that the QMCS DIW cooling system has about five times as much water volume as the largest RCCS cooling system.

The QMCS polishing closed loop consists of the following components (see Figures 4 and 5) [6]:

- a 5 µm prefilter
- two dissolved oxygen ion exchange resin bottles
- two mixed-bed demineralizer ion-exchange resin bottles
- a UV light
- a 1 µm afterfilter

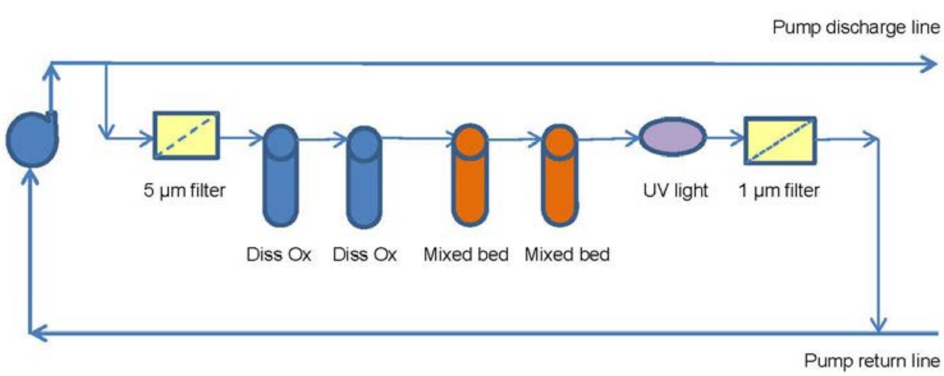

Figure 4. QMCS polishing loop.

Figure 5. QMCS polishing loop components.

4.3.2 RCCS/QMCS Makeup Loops

The makeup loops only run when water needs to be added to the RCCS/QMCS system (when the pump suction pressure decreases).

The typical RCCS/QMCS makeup water polishing loop consists of the following components (see Figures 6 and 7) [6]:

- a carbon bed ion-exchange resin bottle
- a dissolved oxygen ion exchange resin bottle
- two mixed-bed demineralizer ion exchange resin bottles
- a resistivity limit signal light
- a 5 µm filter

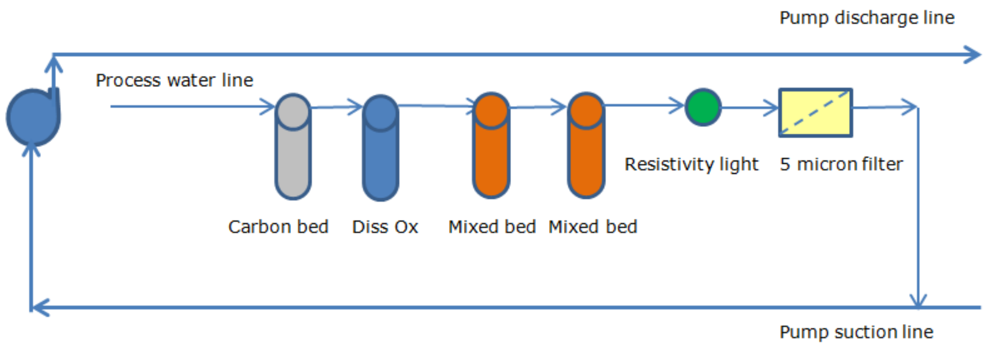

Figure 6. RCCS/QMCS makeup water polishing loop.

Figure 7. Typical makeup line for RCCS DIW loops.

The RCCS/QMCS makeup water is supplied from the process water line in the Klystron Gallery. The polishing loops are housed in the Klystron pump rooms (see Table 5) [6]. All the DTL RCCS systems have one common makeup system with the KL-05 cooling system and are housed in the KL-04 and KL-05 pump room. The CCL RCCS systems have also one common makeup system, shared with the KL-01 DIW system. It is housed in the KL-01 pump room. The QMCS cooling system shares the makeup with the KL-03 DIW system and it is housed in the KL-03 pump room.

Table 5. Locations of the RCCS/QMCS makeup polishing loops.

DTL-1, DTL-2, DTL-3 DTL-4, DTL-5, DTL-6	In KL-04 and 05 pump room, next to KL-05 glycol skid
CCL-1, CCL-2, CCL-3, CCL-4	In KL-01 pump room
QMCS	In KL-03 pump room

Source: K. Magda, *RCCS/QMCS Chemistry Guidance Document*, 2017.

5. DESCRIPTION OF WATER CHEMISTRY VARIABLES

The cooling-channel corrosion rate is a function of several variables:

- water flow velocity;
- dissolved oxygen concentration in the water, which can be
  - low oxygen or
  - air saturated;
- water pH, which can be
  - neutral (7)
  - acidic (< 7)
  - basic pH (> 7), and
- water resistivity.

The SNS RCCS/QMCS water systems operate in conditions of low oxygen, high resistivity, and close to neutral pH. The pH is a function of resistivity and oxygen concentration in the water.

Figure 8 shows that the corrosion rate is a function of oxygen concentration in the cooling water [8].

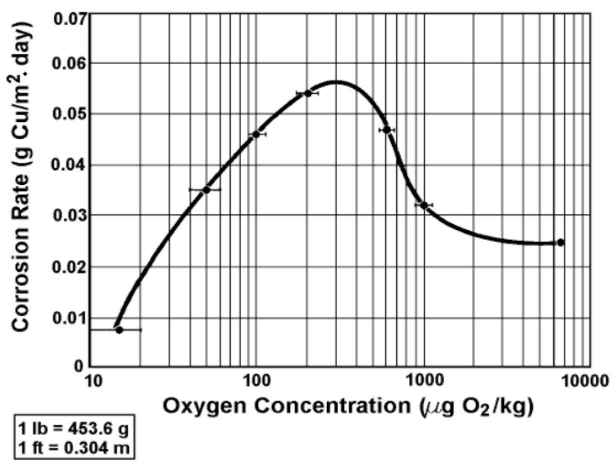

Figure 8. Corrosion rate as a function of oxygen concentration. Source: P. H. Effertz and W. Fichte, “Beeinflussung der Kupferkorrosion in hochreinem Wasser” (“Influencing Copper Corrosion in High-Purity Water”), *Jahrbuch Vom Wasser,* 1974.

From Figure 9 [9] it can be concluded that the corrosion rate is highest when the oxygen concentration is the range of about 50 to 600 ppb O_2 and that the corrosion rate decreases when the water is mildly alkaline (shown by the two bottom curves for pH = 8 and 8.5). It is recommended that the oxygen concentration be kept below 30 ppb O_2 or in the higher region, above 1,000 ppb O_2.

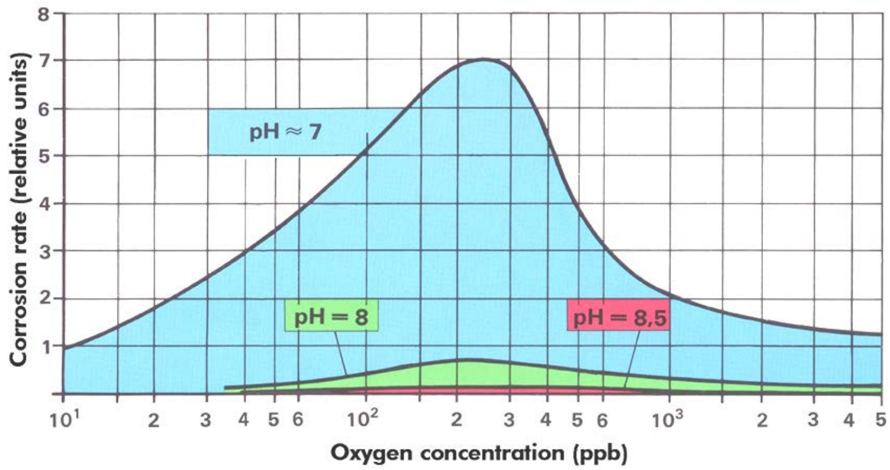

Figure 9. Copper release rate as a function of oxygen concentration and pH. Source: B. B. Syrett and J. Stein, *Prevention of Flow Restrictions in Generator Stator Water Cooling Circuits,* EPRI Technical Report, 1006684, final report, 2002.

The copper corrosion rate for the cooling channels is higher when the flow velocity is higher (see Figure 10) [10].

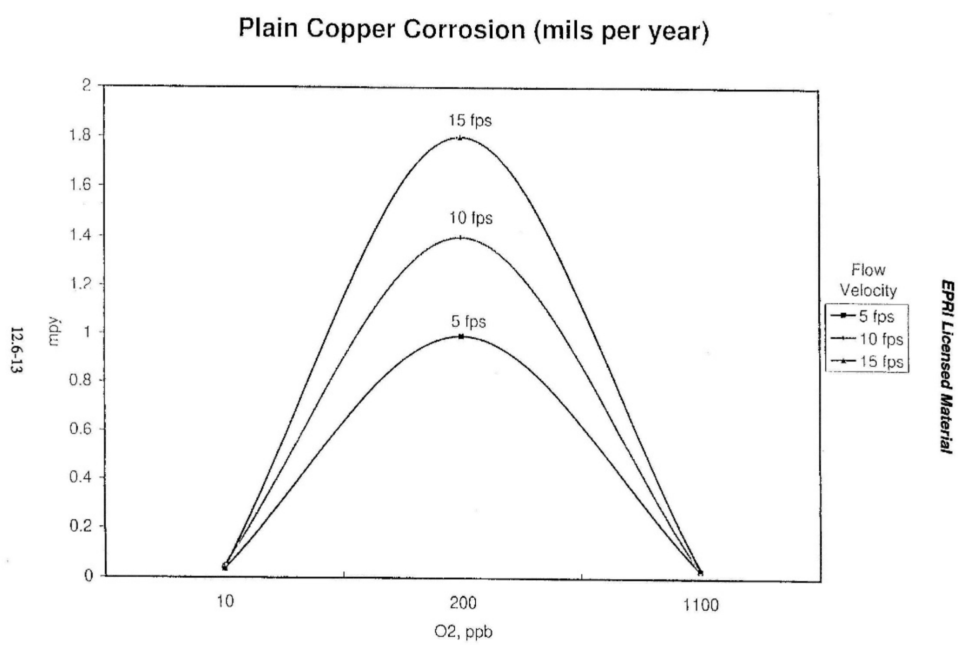

Figure 10. Plain copper corrosion (mil/year). Source: *Primer on Maintaining the Integrity of Water-Cooled Generator Stator Windings,* EPRI TR-105504, 12.6-13, 1995.

Figure 11 [11] shows the copper release rate as a function of pH and oxygen concentration. Colors are used in the figure to show four fields with different copper-release rates.

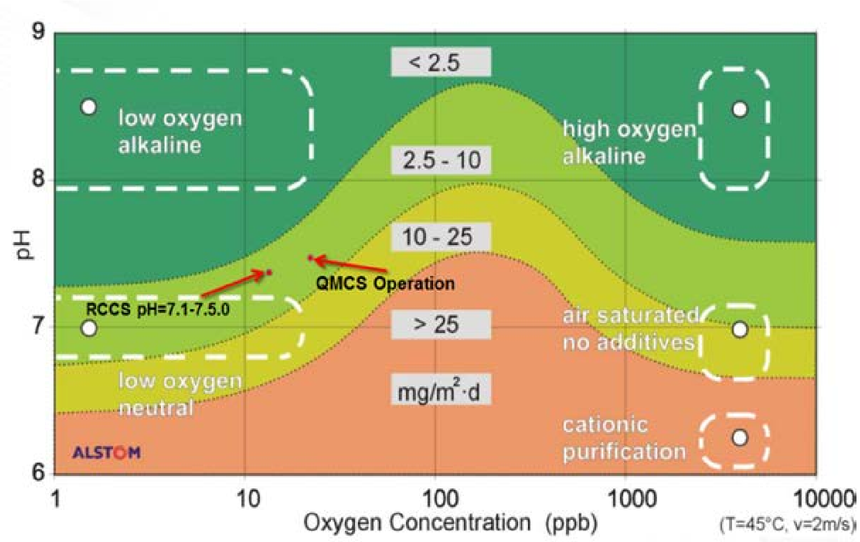

Figure 11. Corrosion rate at various operating regimes. Source: Robert Svoboda,, *Review of Cooling Water Chemistry at ORNL/SNS*, SNS-NFDD-ENG-TR-001-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 2010. (adapted and altered).

Figure 11 also shows that five basic operation regimes can be characterized:

- low-oxygen neutral
- low-oxygen alkaline
- high-oxygen alkaline
- air-saturated neutral (with no additives)
- cationic purification

It can be concluded that the most favorable regimes are in low-oxygen alkaline and high-oxygen alkaline fields, as indicated by the dark green region in Figure 11. The RCCSs are operating in a low-oxygen region and in a mildly alkaline regime (pH = 7.1–7.5), as shown by the red dot labeled “RCCS” to the left in the light green area of Figure 11. The QMCS operates with somewhat higher pH and higher dissolved oxygen region (the red dot labeled “QMCS Operation”).

Figure 12 [12] shows the relationship of the DIW pH and resistivity. It also shows the maximum possible DIW resistivity of 18.24 MΩ-cm at pH 7 at the temperature of 25°C. The vertical red line drawn in the chart shows an average pH of 7.3 for the RCCS lines; the horizontal red line shows an average resistivity of 15.3 MΩ-cm for the RCCS lines.

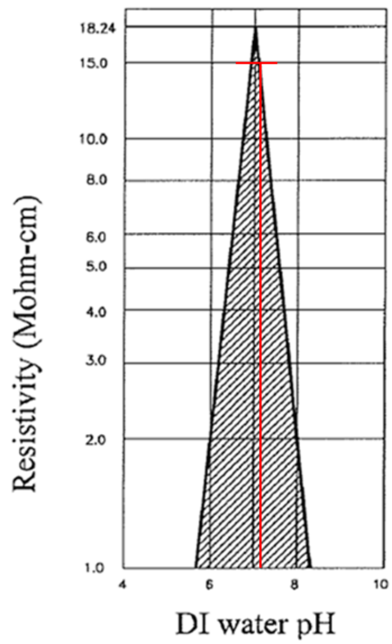

Figure 12. Resistivity Limits of DIW. Source: R. Dortwegt and E.V. Maughan, *The Chemistry of Copper in the Water and Related Studies Planned at the Advanced Photon Source*, College of Knowledge, Duisburg, Germany.

Figure 13 [11] is similar to Figure 12; however, Figure 12 shows the relationship between conductivity and pH for DIW. A scale for resistivity was added to the right side of Figure 13. Figure 13 shows the possible and impossible regions for pH data as a function of conductivity (resistivity).

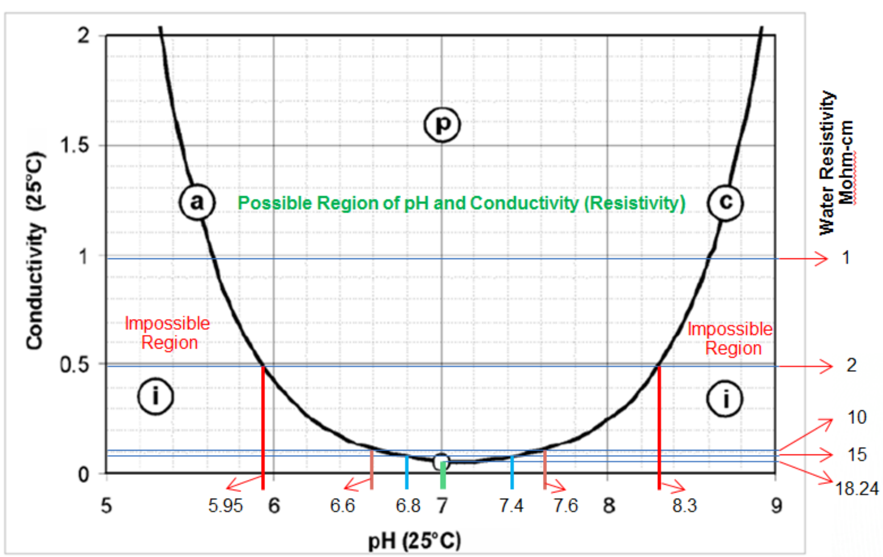

Figure 13. Conductivity (µS/cm) versus pH: (a) relations for strong acids, (c) relations for strong caustics, (i) impossible region, (p) region for all possible electrolytes. Source: Adapted from R. Svoboda, *Review of Cooling Water Chemistry at ORNL/SNS*, SNS-NFDD-ENG-TR-001-R00, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 2010.

6. METHODS OF DIW CHEMISTRY DATA COLLECTION

The RCCS/QMCS data for the DIW pH, dissolved oxygen content, and temperature are collected by instrumentation installed on portable chemistry carts (see Figure 14). The values for pH, dissolved oxygen content, and temperature of the DIW can be read from the displays on the chemistry carts (see Figure 15.) The instrumentation and displays for DIW resistivity are located on the pump skids (see Figure 16).

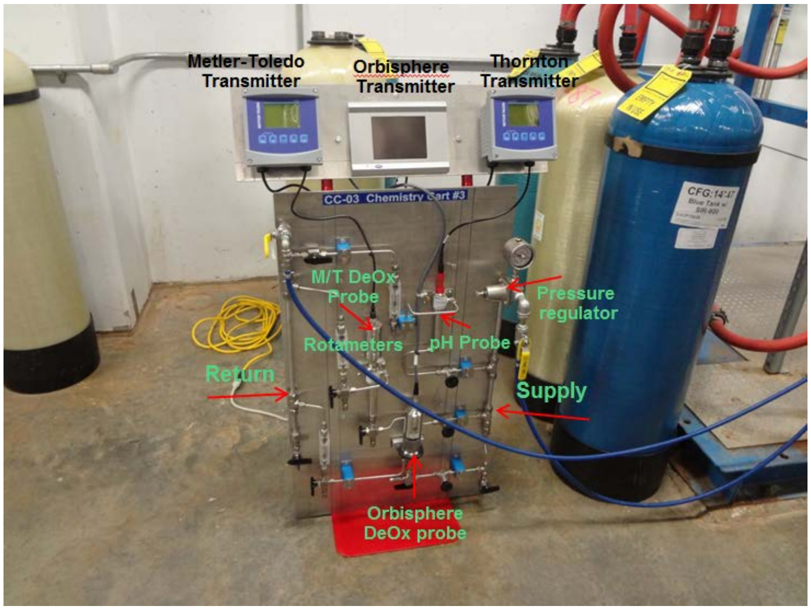

Figure 14. Example of a chemistry cart.

Figure 15. Readouts showing pH and temperature (left) and dissolved oxygen (right).

Figure 16. Readouts for the water resistivity meters. RT 1 measures the main loop water resistivity; RT 2 measures the water resistivity after polishing.

7. CHEMISTRY ANALYSIS SUMMARY

RCCS/QMCS DIW data collected during a 2 year observation period (August 2014 to July 2016) are discussed in this section. Average for pH, resistivity, dissolved oxygen, polishing loop flow, percentage of polishing loop flow in relation to main loop flow, and discharge temperature as well as the grand average for each are listed in Table 6. The data averages are displayed graphically in Figures 17 through 22.

Table 6. RCCS/QMCS DIW chemistry data averages collected by chemistry carts, August 2014–July 2016.

Monitored system	pH	Resistivity (MΩ-cm)	Dissolved oxygen (ppb)		Polishing loop Flow (GPM)	Flow rate by system (GPM)	Percentage of total flow (%)	Discharge Temperature (°F)
			Thornton	Orbisphere				
DTL-1	7.17	13.87	70.97	56.43	4.02	118	3.41	73.99
DTL-2	7.20	16.08	13.55	11.73	4.03	185	2.18	64.04
DTL-3	7.12	14.52	14.06	9.57	4.04	243	1.66	76.25
DTL-4	7.20	16.38	27.99	26.67	4.00	219	1.83	57.49
DTL-5	7.24	16.51	21.53	19.05	4.04	200	2.02	62.03
DTL-6	7.22	17.26	6.29	5.53	3.96	195	2.03	57.39
CCL-1	7.37	15.52	9.56	4.78	4.00	221	1.81	71.39
CCL-2	7.47	15.36	8.06	1.92	4.06	233	1.74	68.47
CCL-3	7.50	14.44	16.60	6.75	4.48	249	1.80	73.53
CCL-4	7.44	14.64	2.35	0.00	4.06	241	1.68	74.36
QMCS	7.42	13.62	46.80	30.63	6.04	257	2.35	71.95
Grand average	7.30	15.29	21.61	15.73	4.25	215	2.05	68.26

Figure 17 presents the pH average values for the individual cooling systems and the average of all systems. DTL-3 shows the lowest pH (7.12); CCL-3 shows the highest (7.50). The grand average is 7.30). All of the pH values are within the optimal boundaries (7.0–9.0).

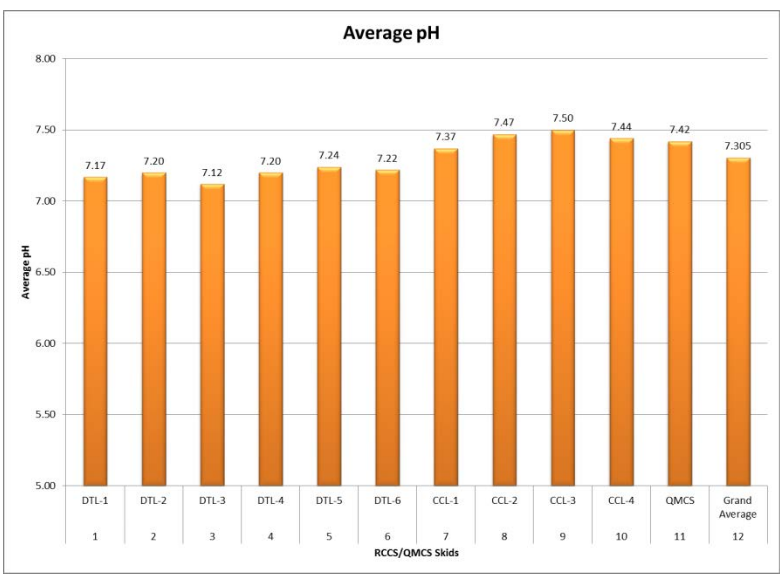

Figure 17. Average pH values per line and the grand average for the observation period.

Figure 18 presents the average resistivity for the individual cooling systems and the average of all systems. QMCS shows the lowest resistivity (13.62 MΩ-cm); DTL-6 shows the highest (17.26 MΩ-cm). The grand average is 15.29 MΩ-cm. All of the resistivity values are > 12 MΩ-cm.

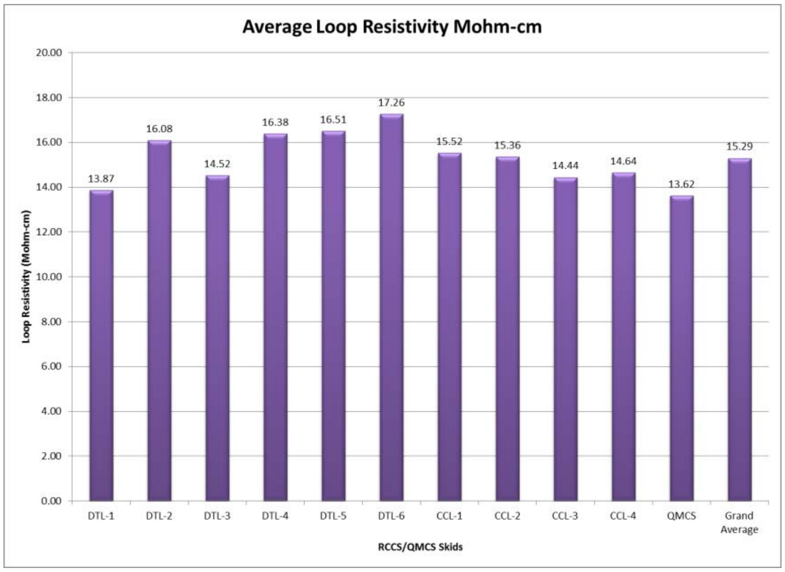

Figure 18. Average resistivity values per line and the grand average for the observation period.

Figure 19 presents the average dissolved oxygen values for the individual cooling systems and the average of all systems. Thornton instrumentation was used to obtain the data. CCL-4 shows the lowest concentration (2.35 ppb O_2); DTL-1 shows the highest (70.97 ppb O_2). The grand average is 21.61 ppb O_2.

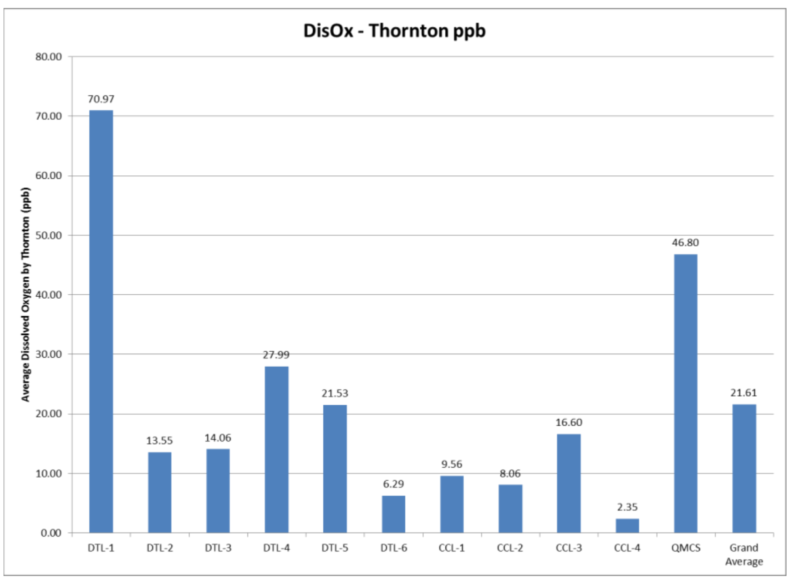

Figure 19. Average dissolved oxygen content values per line and the grand average for the observation period. Thornton instrumentation used to obtain the data.

Figure 20 presents the average dissolved oxygen values for the individual cooling systems and the grand average of all the systems. Orbisphere instrumentation was used to obtain the data. CCL-4 shows the lowest value (0.00 ppb O_2); DTL-1 shows the highest (56.43 ppb O_2). The grand average is 15.73 ppb O_2.

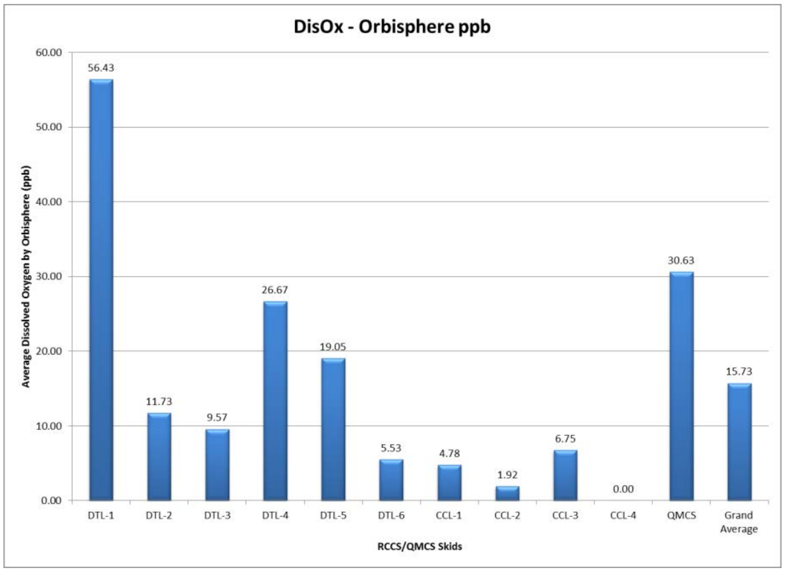

Figure 20. Average dissolved oxygen content values per line and the grand average for the observation period. Orbisphere instrumentation was used to obtain the data.

Data from the two instruments that were used to measure dissolved oxygen concentrations show some differences; however, both show that the content is lowest in the CCL-4 cooling system and that it is highest in DTL-1. All but two of the systems are in the desired range (< 30 ppb O_2). DTL-1 and QMCS are the exceptions.

Additional data analysis revealed that the measured values for dissolved oxygen in DTL-1 were very high in mid-February 2014 and in mid-August 2015. The values increased sharply and then decreased sharply. The values were in the normal range before and after those spikes. Because of the high values in August and February, the average dissolved oxygen content was much higher for DTL-1 than it was any other RCCS system. It is thought that the DissOx instruments were out of calibration. Currently, the DTL-1 dissolved oxygen values are < 20 ppb.

Figure 21 presents the average temperature values for the individual cooling systems and the average of all systems. DTL-6 shows the lowest temperature [57.39°F (14.1°C)], DTL-3 shows the highest [76.25°F (24.6°C)]. The grand average is 68.26°F (20.1°C).

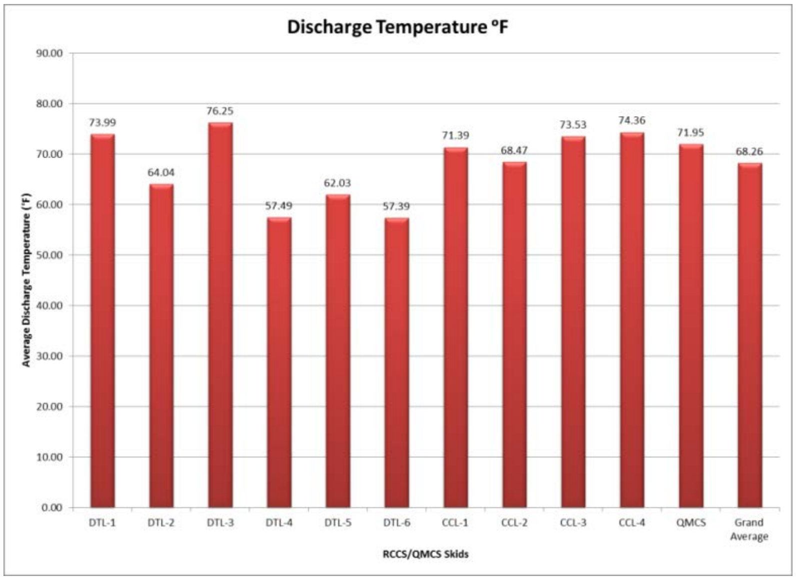

Figure 21. Average water temperature values for the individual cooling systems and the grand average for the observation period (in degrees Fahrenheit).

Figure 22 presents the average flow in the individual polishing loops and the average of all flow values. Most of the RCCS lines average a flow of about 4 GPM, except CCL-3, which averages about 4.5 GPM. The average flow for the QMCS system was about 6.1 GPM during the observation period.

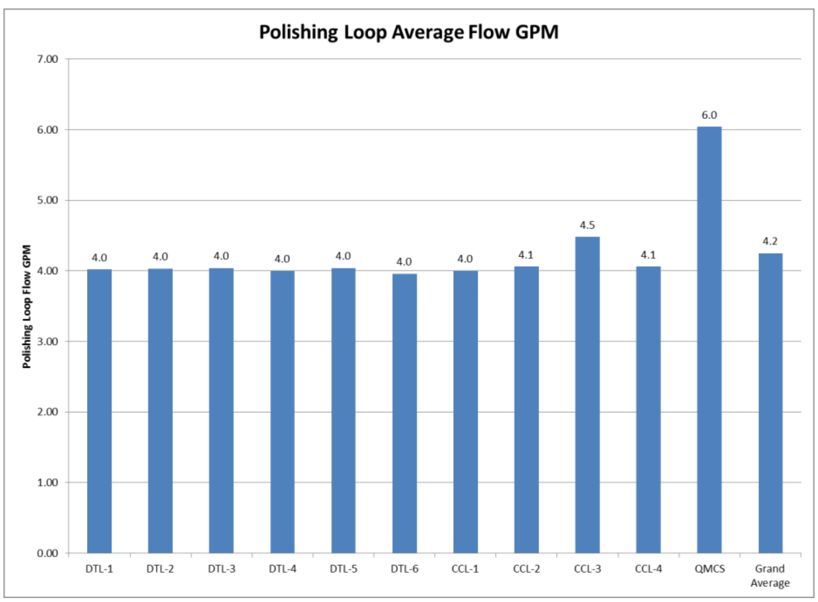

Figure 22. Average flow values per line and the grand average for the observation period (in gallons per minute).

8. POLISHING LOOPS PREFILTER CHEMICAL ANALYSIS

Chemical analysis of material collected in the polishing-loop prefilters is used to monitor the RCCS/QMCS DIW chemistry and to collect data (see Figure 23). The chemical analysis of filter deposits started in 2013. MCL Inc. chemically analyzes the used prefilters after the periodic accelerator outages. The purpose of the analysis is to determine the composition of the residue found on the filters. The analysis includes the determination of particle size and quantity in addition to chemical makeup [13].

Figure 23. the RCCS/QMCS used prefilters removed from polishing loops in summer outage 2016. The lighter filters are loaded with less particulate matter than the darker filters. Iron particles are dominant in the dark grey filters (e.g., DTL-4); copper particles are dominant in the brownish filters. (Photographs provided by Materials and Chemistry Laboratory, Inc.)

Variations in iron and copper caught in prefilters are of primary importance for tracking erosion and corrosion of the copper structure and of steel and other components of the accelerator cooling skids. The filter load (increase or decrease of material trapped on the filters) is trended. The prefilter analysis includes the following steps (see Figures 24 and 25):

- The loading factor (percentage of area coverage on filters) is calculated.
- X-ray diffraction (XRD) is used to identify the crystalline phases in particulates.
- Scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) are used to determine the chemical composition of the particulates.

Seven metals of interest are considered to be critical: iron (Fe), chromium (Cr), nickel (Ni), copper (Cu), silicon (Si), aluminum (Al), and potassium (K). The seven elements are grouped into the following categories:

- stainless steel (Fe-Cr-Ni),
- copper (Cu), and
- silicate components (Si-Al-K).

The particulates are typically enriched in Fe, Cu, Si, and Al. An increase of copper in the filter load might indicate erosion or corrosion of the copper structure cooling channels. Silica carbide might indicate the failure of skid components such as pump bearings, impellers, and valve seats.

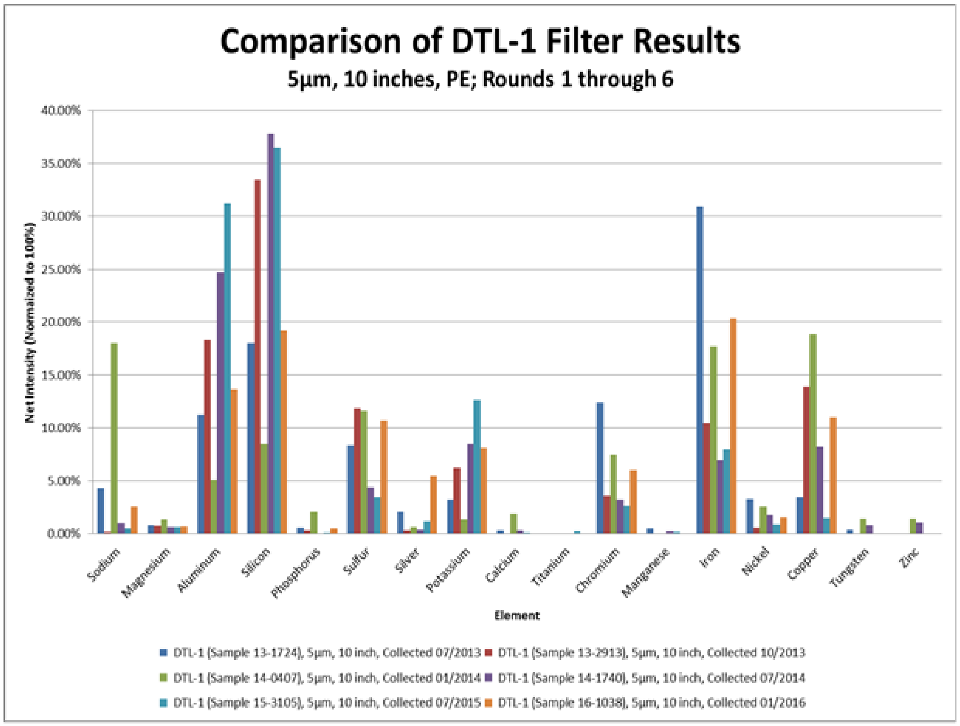

Figure 24. Comparison of the results from six rounds of analysis of the DTL-1 filter.

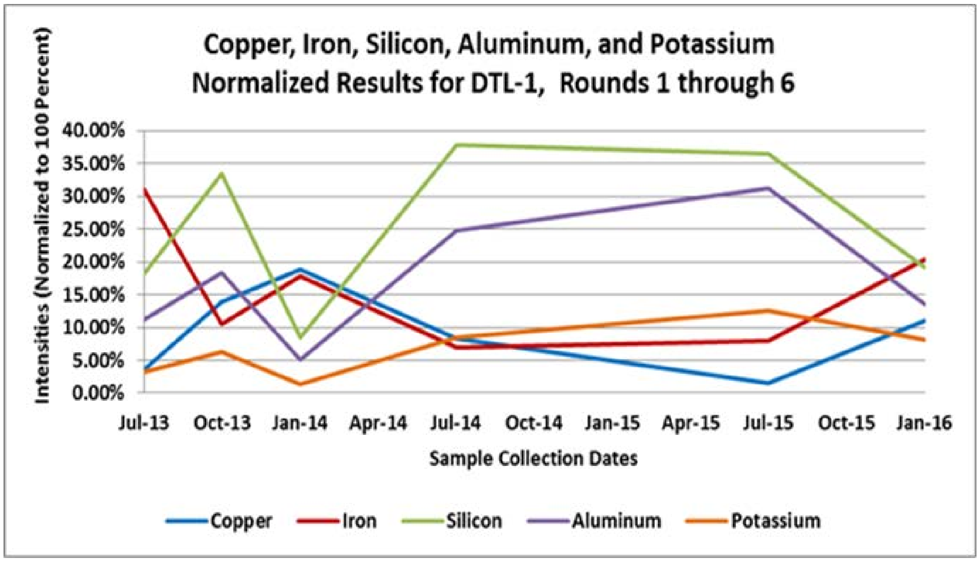

Figure 25. Trends of major material components found on DTL-1 in six analysis rounds. The sums of the percentages of major material components and sum of the minor components are equal to approximately 100% of filtered material for each analysis date.

8.1 SIGNIFICANCE OF THE PREFILTER ANALYSIS

One importance of the prefilter analysis is its role in predicting failure of the RCCS/QMCS cooling components (see Figures 26 and 27).

Figure 26. Damaged silica carbide thrust bearing on the DTL-3 pump. Silicon trapped on the prefilter is material worn or chipped off the circulating pump thrust bearing.

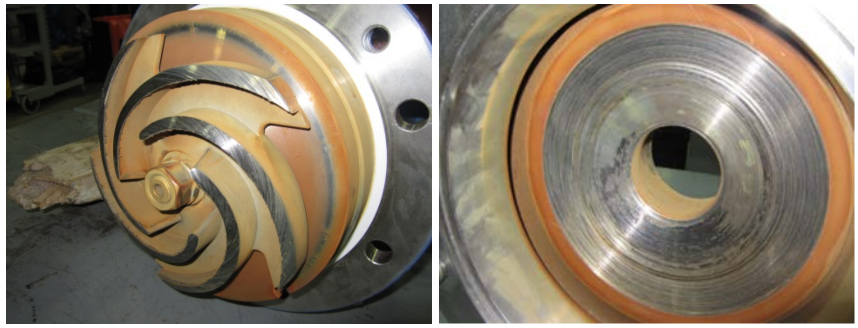

Figure 27. Damaged impeller and volute of the DTL-3 pump. Iron particles that collected on the prefilter are worn off or chipped off the RCCS/QMCS impeller and volute as they collided.

9. CONCLUSION

The cooling water chemistry data available for the observed period indicate that the corrosion rate for the RCCS/QMCS is reasonably low and that an effective DIW chemistry treatment is being practiced. Figure 11 shows the average point of operation for all RCCS and QMCS cooling water chemistry operation regime. The average pH for all RCCS skids is 7.29, and average dissolved oxygen in water is 14.24 ppb O_2 for the observed period. On the chart this point of operation is within the light green field, and the corrosion rate is between 2.5 and 10 mg/m^2 day and it is estimated 5 mg/m^2 day, which equals 0.0081 mil/y.

The QMCS average pH is 7.42; the average dissolved oxygen in water is 30.63 ppb O_2 as measured by Orbisphere instrument and 46.8 ppb O_2 as measured by the Thornton instrument. As shown in Figure 11, the QMCS chemistry operation is in the same light green field with the corrosion rate, between 2.5 and 10 mg/m^2 day and it is estimated 8 mg/m^2 day, which equals 0.0129 mil/y.

For all RCCS and QMCS systems in this chemistry operation regime the water is mildly alkaline and the amount of dissolved oxygen is low. This operation regime is favorable, and the corrosion rate is low. The analysis confirms that the RCCS and QMCS cooling water chemistry is being managed properly.

10. RECOMMENDATION

The recommendation is to continue current RCCS/QMCS polishing to maintain the following chemistry values:

- high resistivity: > 15 MΩ-cm
- low oxygen: < 50 ppb
- midrange pH: 7–7.5

The advantage of this practice is that a low dissolved oxygen level in water and slightly alkaline environment results in a low corrosion rate of the cooling channels. This chemistry protocol for the RCCS/QMCS cooling systems takes advantage of years of operational experience and lessons learned.

It is also recommended that the prefilters chemical analyses continue.

It is suggested that more attention be paid to DTL-1 and QMCS dissolved oxygen content in the future.

11. REFERENCES

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APPENDIX A. DIW ION EXCHANGER RESINS



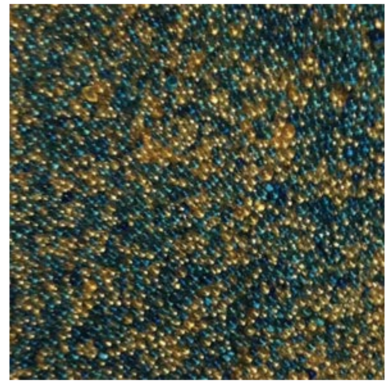

Figure A1. ResinTech ion exchange resins. Left: AGC-40 AW carbon bed resins. Center: SIR-800 oxygen scavenger resin. Right: MBD-10 mixed-bed resins. *Source:* https://www.resintech.com/ion-exchange-resins.

Table A.1. RCCS/QMCS cooling water systems ion exchanger resin beds.

Ion Exchanger Type	**Resin**				
	Name	**Type**	**Physical properties**	**Application**	**Mechanism**
Carbon bed	AGC-40	Granulated activated carbon	Coal-based granules	Dechlorinate water, reduce organic impurities	Adsorption in carbon pores
Dissolved oxygen removal	SIR-800	Gel anion resin, sulfite form, strong base	Polymer structure: styrene/DVB	Remove dissolved oxygen from water	Conversion of sulfite to sulfate
Mixed-bed 2:3 cation/anion	MBD-10	Mixture of strong acid cation resin and a strong base anion resin	Polymer structure: styrene/DVB	Remove total dissolved solids	Replacment of H ions with positively charged ions and OH ions with negatively charged ions

APPENDIX B. IMAGES FROM THE LINAC TUNNEL: DTL, CCL, AND QMCS COOLING STRUCTURES

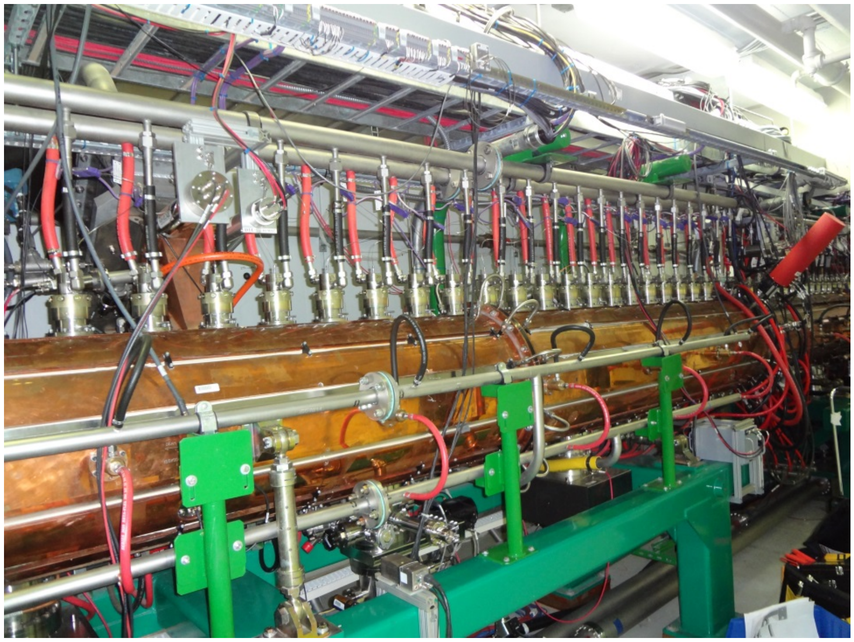

Figure B1. DTL structure in the linac tunnel.

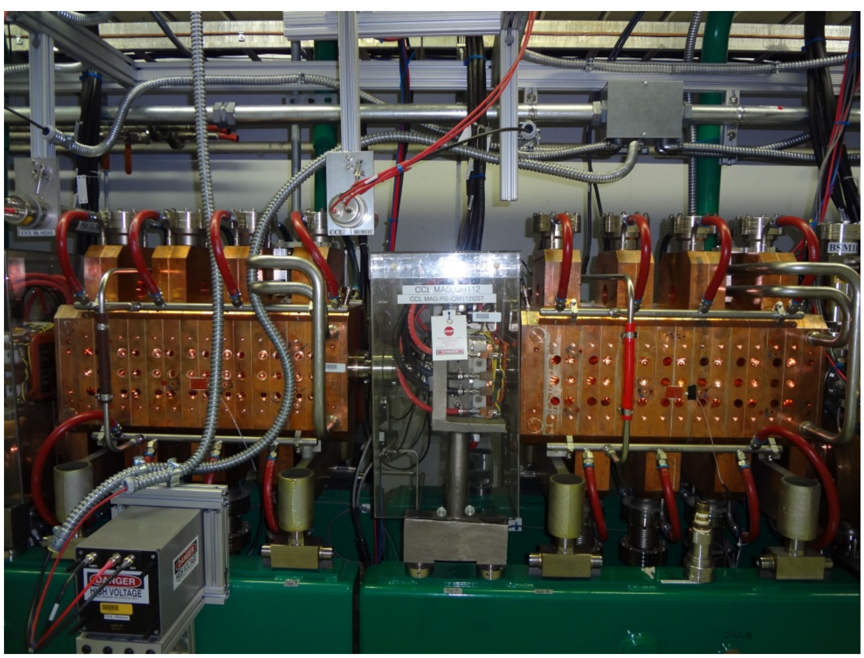

Figure B2. CCL structure in the linac tunnel.

Figure B3. QMCS magnet cooling in the linac tunnel.